Measurement of the W-Boson Mass

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We have determined $m_W = 79.91 \pm 0.39$ GeV/c^2 from an analysis of $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ data from the Collider Detector at Fermilab in $\bar{p}p$ collisions at a c.m. energy of $\sqrt{s} = 1.8$ TeV. This result, together with the world-average Z mass, determines the weak mixing angle to be $\sin^2\theta_W = 0.232 \pm 0.008$. Bounds on the top-quark mass are discussed.

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The masses m_W and m_Z of the vector bosons are fundamental parameters in the standard electroweak model.[1-3] Together, they determine the weak mixing angle through its definition,[4,5] $\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$, and give an upper limit on the mass of the, as yet, unobserved top quark. The measured value of the W mass reported here is based on a sample of 1130 $W \rightarrow e\nu$ and 592 $W \rightarrow \mu\nu$ candidate events in the Collider Detector at Fermilab (CDF) from integrated luminosities of 4.4 and 3.9 pb^{-1}, respectively, in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV at the Tevatron Collider. Details of the W mass analysis, summarized here, may be found in Ref. 6.

The components of the CDF relevant for this analysis are described briefly here. A detailed description of the detector may be found in Ref. 7. Charged tracks are measured with vertex time-projection chambers (VTPC) and a central tracking chamber (CTC) in a 1.4116-T solenoidal magnetic field. Scintillator-based electromagnetic (EM) and hadronic (HAD) calorimeters in the central region, pseudorapidity $|\eta| < 1.1$, are arranged in a projective tower geometry. The cell sizes in η and azimuthal angle ϕ are $\Delta\eta \times \Delta\phi = 0.1 \times 15°$. Muon drift chambers reside behind the calorimeters in the region $|\eta| < 0.63$. Gas-based calorimeters are used in the region $1.1 < |\eta| < 3.6$.

Charged-particle momenta are determined in the CTC with an rms resolution of $\delta p_T/p_T = 0.0011 p_T$ (p_T in GeV/c). An overall momentum scale uncertainty of 0.1% is determined from an analysis of muon pairs in J/ψ and Υ candidates. Electron transverse energies are measured with an accuracy of $\delta E_T/E_T = [(0.135/\sqrt{E_T})^2 + (0.020)^2]^{1/2}$, where E_T is in GeV. The cell-to-cell relative normalization of the EM calorimeters is obtained by analyzing a large sample of inclusive electron events. The overall energy scale is normalized with an accuracy of 0.24% to the CTC momentum scale by fitting the energy-to-momentum ratio E/p of a sample of W electrons.[6]

The trigger for the electron sample required at least 12 GeV transverse electromagnetic energy in the central calorimeter, associated with a track in the CTC of transverse momentum $p_T > 6$ GeV/c. The muon trigger required a track stub in the muon drift chambers behind the central calorimeter modules, matched to a CTC track of $p_T > 9$ GeV/c. Electrons are restricted to the region $|\eta| < 1.0$ and muons to $|\eta| < 0.6$. The trigger is fully efficient in the kinematic range of interest.

The transverse momentum of the neutrino p_T^ν is inferred from the vector imbalance of the calorimeter E_T and charged-lepton momentum. We do this by constructing the vector

$$\mathbf{u} = \sum_i E_i \sin\theta_i \, \hat{\mathbf{n}}_i \, ,$$

where E_i is the total (electromagnetic plus hadronic) energy in the ith tower. The polar angle θ_i and the unit vector in the transverse plane $\hat{\mathbf{n}}_i$ are calculated using the event vertex and the center of the tower. The cells containing the charged-lepton energy are not included in the sum. The vector $\mathbf{u}$ and the charged-lepton momentum p_T^l determine the neutrino transverse momentum $\mathbf{p}_T^\nu = -k_u \mathbf{u} - \mathbf{p}_T^l$. The factor $k_u = 1.4$ multiplying $\mathbf{u}$ scales the calorimeter low-energy response to that of the charged leptons.[8] The resolution for each component of $\mathbf{u}$, determined from studies of minimum-bias events, is $\sigma_u = 0.47\sqrt{\sum E_T}$, where $\sum E_T$ is the total, uncorrected, scalar E_T in the calorimeter, not including the charged leptons. The constant 0.47 in the expression has units of GeV$^{1/2}$; σ_u and E_T have units of GeV.

The event samples used to determine the W mass require $p_T^l > 25$ GeV/c and $p_T^\nu > 25$ GeV/c. Events were removed if any cluster[8] of raw calorimeter transverse energy greater than 5 GeV was within ±30° opposite in azimuth to the lepton. To minimize the impact of the resolution in the $\mathbf{u}$ measurement, we required no cluster anywhere in the calorimeter above 7 GeV transverse energy other than that containing the electron. To avoid mismeasured Z decays, events with any track above 15 GeV/c p_T other than the lepton track were eliminated from the samples. For the muon sample, the cosmic-ray background was reduced by requiring no track with p_T above 10 GeV/c within ±3° opposite the muon and no other stub in the muon drift chambers consistent with a cosmic ray. A match consistent with multiple scattering was required between the central track and the muon stub. The electron was required to be within the calibrated fiducial region of the central EM calorimeter,[9] to have $E/p < 1.4$, and to be inconsistent with a photon conversion. The final samples contain 1130 electron and 592 muon candidates.

The W mass is obtained from a maximum-likelihood fit of the transverse mass distributions with simulation predictions. The transverse mass is defined as $m_T = [2p_T^l p_T^\nu(1 - \cos\phi_{l\nu})]^{1/2}$, where $\phi_{l\nu}$ is the difference in ϕ between the charged-lepton and neutrino directions. The predictions are an interpolation of a grid in mass and width generated by a Monte Carlo simulation. There is no systematic offset attributable to the fitting procedure. When the width of the W is not constrained, there is a 20%–40% correlation between the W width (or equivalently the detector resolution) and the W mass.

We constrained the width to $\Gamma = 2.1$ GeV to remove some of this sensitivity.

The Monte Carlo model includes dynamics of W production and decay as well as detector response. The model assumes that the W boson is accompanied by a hadronic system that consists of a cylindrically symmetric component and a component that recoils against the transverse momentum of the W. The **u** resolution of the cylindrical component is determined from a sample of minimum-bias-triggered events. The **u** resolution of the recoil component is determined from the study of a sample of Z events for which it is possible to completely reconstruct the gauge-boson transverse momentum.

Using the resolution parameters, an input transverse-momentum distribution of the W, p_T^W, was chosen such that the observed p_T^W distribution was returned by the model. Independent variation of each parameter indicated uncertainties in the W mass of 70 MeV/c^2 due to uncertainties in the electron energy resolution, and 80 MeV/c^2 from the uncertainties in the muon resolution. An additional uncertainty of 130 MeV/c^2 due to resolution modeling is common to both samples.

A variety of parton distribution functions[10-13] have been used to determine a possible bias in assumptions about the distribution in longitudinal momentum. The variations in the fitted W mass are of the order of 60 MeV/c^2. We use the Martin-Roberts-Stirling[13] set B as the nominal set and assign an associated systematic uncertainty on the mass of the W of 60 MeV/c^2.

As the Monte Carlo model does not simulate all details of the component of **u** parallel to the charged lepton, $u_\parallel$, a constant offset $u_\parallel^0$ is introduced to match the average value of the data. An accurate determination of $u_\parallel^0$ is important since its value enters directly into the calculation of p_T^ν and m_T. The values of $u_\parallel^0$, determined by using events with transverse masses above 50 GeV/c^2, are -76 ± 115 and -115 ± 150 MeV/c for the electron and muon samples, respectively. Systematic uncertainties in these values are derived by varying the model parameters and m_T cutoff in the event samples. Details may be found in Ref. 6. We assign overall uncertainties in the W mass due to this effect of 170 and 240 MeV/c^2 for the electron and muon samples, respectively.

Residual backgrounds in the electron sample are less than 1%. The rates from τ sequential decays are negligible. A 1% residual flat background due to cosmic rays is possible in the muon sample. There is a small (<4%) background in the muon sample due to Z's with a missing second track, but these events tend to have large rapidities and yield relatively soft leptons. We conclude 50 and 110 MeV/c^2 are the uncertainties in the W mass due to background in the electron and muon samples. Table I summarizes the uncertainties in our measurement.

The observed and fitted transverse-mass distributions are shown in Fig. 1. The fitting range in m_T is 65–94 GeV/c^2. Corrected for wide-angle radiative effects[14] (70 and 125 MeV/c^2 for the electron and muon samples), the results are

TABLE I. Uncertainties, in units of MeV/c^2, in the W mass measurement. The uncertainties which are the same for both samples are listed as common.

Uncertainty	Electrons	Muons	Common
Statistical	350	530	
Energy Scale	190	80	80
(1) Tracking chamber	80	80	80
(2) Calorimeter	175		
Systematics	240	315	150
(1) Proton structure	60	60	60
(2) Resolution, W p_T	145	150	130
(3) Parallel balance	170	240	
(4) Background	50	110	
(5) Fitting	50	50	50
Overall	465	620	

$$m_W^e = 79.91 \pm 0.35(\text{stat}) \pm 0.24(\text{syst}) \pm 0.19(\text{scale})\ \text{GeV}/c^2$$

and

$$m_W^\mu = 79.90 \pm 0.53(\text{stat}) \pm 0.32(\text{syst}) \pm 0.08(\text{scale})\ \text{GeV}/c^2 .$$

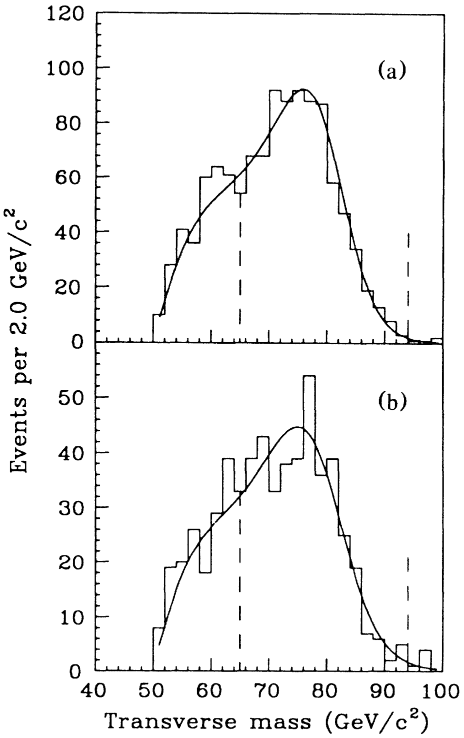

FIG. 1. (a) The transverse-mass distribution for $W \to e\nu$ candidates. Overlaid is the best fit to the data. The range of transverse masses used in the fit is indicated with dashes. (b) The transverse-mass distribution for $W \to \mu\nu$ candidates.

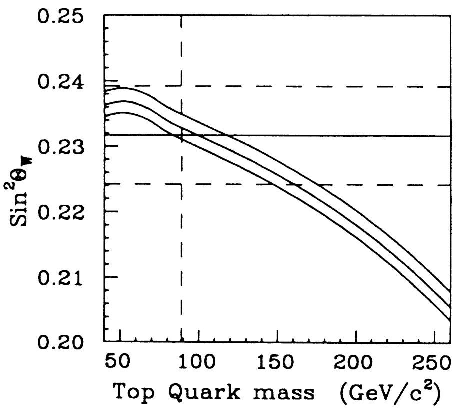

FIG. 2. The relationship between the top-quark mass and $\sin^2\theta_W$ with the Z mass constrained to 91.15 GeV/c^2. The curves (Ref. 18), from top to bottom, correspond to Higgs-boson masses of 1000, 250, and 50 GeV/c^2. The horizontal dotted lines correspond to the 1σ uncertainties. The vertical dotted line at 89 GeV/c^2 corresponds to the CDF top-quark mass limit (Ref. 19).

We have checked sensitivity to cutoffs, subdivided the samples, varied the selection, not constrained the width, and fitted the transverse momenta of electrons, muons, and neutrinos and find no evidence for additional systematic uncertainty. We have confirmed the statistical precision using multiple Monte Carlo samples of the size of the data. The combined result is $m_W = 79.91 \pm 0.39$ GeV/c^2, consistent with previous measurements.[15,16] A division of the data into positively and negatively charged W's yields $m_W^+ - m_W^- = -0.19 \pm 0.58$ GeV/c^2, consistent with *CPT* invariance.

In order to determine the weak mixing angle we combined the W mass values from the electron and muon decays with the world-average Z mass[17] of 91.161 GeV/c^2 to obtain $\sin^2\theta_W = 0.2317 \pm 0.0075$. Figure 2 shows the relationship between the top-quark mass and $\sin^2\theta_W$. For a Higgs-boson mass lighter than 1000 GeV/c^2 the top-quark mass is constrained, within the context of the minimal standard model, to be $m_{\text{top}} < 220$ GeV/c^2 (95% C.L.). Combining our value with that of UA2 (Ref. 16) yields $\sin^2\theta_W = 0.227 \pm 0.006$.

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